Precision measurement of the neutron $\beta$-decay asymmetry


(UCNA Collaboration)

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A new measurement of the neutron $\beta$-decay asymmetry $A_0$ has been carried out by the UCNA Collaboration using polarized ultracold neutrons (UCNs) from the solid deuterium UCN source at the Los Alamos Neutron Science Center. Improvements in the experiment have led to reductions in both statistical and systematic uncertainties leading to $A_0 = -0.11954(55)_{\text{stat}}(98)_{\text{syst}}$, corresponding to the ratio of axial-vector to vector coupling $\lambda \equiv g_A/g_V = -1.275(30)$.

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$A_0 = -2(\lambda^2 - |\lambda|) / (1 + 3\lambda^2)$,

where $\lambda \equiv g_A/g_V$ is the ratio of the vector to axial-vector weak coupling constants. Combining $g_A$ with independent measurements of the Fermi coupling constant $G_F$, the Cabibbo-Kobayashi-Maskawa matrix element $V_{ud}$, and the neutron lifetime $\tau_n$ allows a precision test of the consistency of measured neutron $\beta$-decay observables [7].

The ultracold neutron asymmetry (UCNA) experiment is the first experiment to use ultracold neutrons (UCNs) in a precision measurement of neutron decay correlations. Following the publication of our earlier results [7–9], the UCNA Collaboration implemented a number of experimental improvements that led to reductions in both statistical and systematic uncertainties. These improvements, described below, include enhanced UCN storage, improved electron energy reconstruction, and continuous monitoring of the magnetic field in the spectrometer. This refined treatment of the systematic corrections and uncertainties begins to address issues of consistency in the world data set for $A_0$.

The UCNA experiment ran in 2010 using the “thin window geometry D” as described in [7,9], and collected a total of $20.6 \times 10^8 \beta$-decay events after all cuts were applied. We used the UCN source [10] in area B of the Los Alamos Neutron Science Center (LANSCE). UCNs were polarized by a 6 T

\[ W(E) \propto 1 + \frac{v}{c} (P) A(E) \cos \theta, \]

where $A(E)$ specifies the decay asymmetry for electron energy $E$, $v \equiv \beta c$ is the electron velocity, $(P)$ is the mean neutron polarization, and $\theta$ is the angle between the neutron spin and the electron momentum. The leading order value of $A(E)$, $A_0$, can be expressed as

\[ A_0 = \frac{-2(\lambda^2 - |\lambda|)}{1 + 3\lambda^2}. \]
Polarized UCNs enter the superconducting spectrometer (SCS) [12] and are confined in a 3 m long, 12.4 cm diameter diamond-like carbon (DLC) coated Cu tube (decay trap) with a 0.7 μm thick Mylar end caps. The inside surface of each end cap is coated with 200 nm of Be to contain the neutrons. A 0.96 T magnetic field is oriented parallel to the decay trap, along which decay electrons spiral toward one of two identical electron detector packages. Between the decay trap and the detectors, the magnetic field expands out to 0.6 T, which reduces the electrons’ transverse momenta and pitch angles, decreasing backscattering from the detectors. Each detector package consists of a 16 cm × 16 cm low-pressure multiwire proportional chamber (MWPC) [13] backed by a 15 cm diameter plastic scintillator, whose scintillation light is detected by four photomultiplier tubes (PMTs). Each MWPC has 6 μm Mylar windows at the front and back that separate the chamber gas (100 torr neopentane) from the spectrometer vacuum and PMT housing (<100 torr N2). Cosmic-ray muon backgrounds are identified by a combination of plastic scintillator veto paddles and sealed Ar/ethane drift tube assemblies [14] around the electron detectors.

A typical run unit consists of a background run (gate valve closed), a β-decay run (gate valve open), and a UCN depolarization run (see below). To partially cancel drifts in background and detector efficiency, we alternate the order of the β-decay and background runs, and organize the asymmetry measurements into octets with a spin flipper on (+), off (−) sequence of −−−−+++− or −−−−+−−-, chosen randomly.

Scintillator event triggers are formed by requiring at least two out of four PMT signals over threshold in either of the scintillator detectors. Due to the low mass of the MWPC, applying an analysis cut requiring coincidence between the MWPC and the scintillator rejects >99% of external γ-ray background. Energy deposition in the MWPC is calibrated against our measurements (“reload” measurements) in which the spin flipper state is toggled for 3 s during the middle of the cleaning phase in order to selectively enhance the signal from the reloaded population. The measured polarization in the case of a spin-flipper-off β-decay run also requires correction for spin flipper inefficiency, which is determined using the difference between polarizations observed for spin-flipper-off and spin-flipper-on along with Monte Carlo calculated scaling factors. Further small corrections for UCN populations detected in the switcher detector with low efficiency are estimated via Monte Carlo and are consistent with separate empirical studies of the system [11]. These corrections include the effect of the primary polarizing magnet analyzing the unloaded UCN population with less than unit efficiency. Based on the global agreement between Monte Carlo simulations and data, an uncertainty of 30% is attributed to all polarization Monte Carlo calculations. An analysis of our fitting procedure to the switcher detector signal during depolarization runs also contributes to the systematic error. This includes sensitivity to the fitting intervals, along with the internal consistency of the extracted time constants.

Midway through the 2010 run, a vacuum pump failure unexpectedly vented the spectrometer, producing pinhole leaks in the MWPC windows. For a brief period of operation before the windows were replaced, neopentane leaking from the wire chambers into the vacuum may have permanently contaminated the UCN guide surfaces, resulting in a change to the UCN transport characteristics of the system (e.g., a 35% reduction of UCN storage lifetime in the decay trap was observed after the pump failure). Since this incident potentially altered the equilibrium UCN polarization in the decay volume, separate polarization analyses for the periods before and after the pump failure were required. In order to improve the statistics, and because there were no observable changes to the experimental geometry between the 2009 run cycle and the pump failure, the set of reloaded population measurements obtained in 2009 was combined with the 2010I data acquired prior to the pump failure. The polarizations determined from the “before” and “after” data sets are shown in Table I.

Reconstructed event energies \(E_{\text{rec}}\) are measured using the signals from the four PMTs attached by light guides to the
scintillator disk in each detector. The position dependence of light transport to each PMT is mapped out by filling the spectrometer volume with neutron-activated xenon. Natural isotopic abundance Xe gas is let into the volume normally used to produce a variety of radioactive Xe isotopes by neutron capture. After pumping the activated Xe out of the source volume, controlled amounts are introduced into the spectrometer volume. By observing the decay spectrum features (mainly the 915 keV Xe transition) and by comparing the measured data to predictions, the position-dependent light transport of the β scintillators is mapped out. The increased statistics available from the Xe data compared to natural Xe used in the previous method of mapping position dependence using conversion electron sources (139Ce, 113Sn, and 207Bi) in the previous method of mapping position dependence using conversion electron sources (139Ce, 113Sn, and 207Bi) in our previous publications [7–9]. Therefore, the uniformity of the magnetic field in the decay region was checked with an NMR probe translated through the field with the central decay trap removed. However, due to electron backscattering [7,17], 3% of the events trigger both scintillators, while 2.5% are detected by both MWPCs but trigger only one of the scintillators. In the first case, the initial direction of the electron can be determined by the relative timing of the triggers, while in the second case a cut based on the energy loss in the trigger side scintillator and MWPC yields an identification efficiency of ~80% based on a Monte Carlo simulation.

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Magnetic field uncertainties in our previous studies [7]. Monte Carlo simulations using the observed field profile provide a correction to the measured asymmetry, similar to analytical estimates of magnetic mirroring for high pitch angle events.

In addition to the ambient backgrounds (measured with the UCN gate valve closed) which are subtracted run-by-run, neutron captures in the vicinity of the detectors can create prompt γ’s and delayed β-decay electrons, generating an irreducible background in the experiment. Observed events beyond the neutron β-decay endpoint after background subtraction, compared to a detailed Monte Carlo analysis of possible neutron capture mechanisms, are consistent with a particular combination of UCN capture on the aluminum surfaces of the detector and on the scintillator disk. From this, a ~0.025 Hz neutron generated background spectrum is deduced in the energy range of the ~25 Hz β-decay signal, which is consistent with a small fraction of UCNs escaping from small gaps in the UCN guides and decay trap, and within limits previously set in [7]. This excess contributes a correction and uncertainty to the measured asymmetry of +0.01(2)%.
subunits therein. Is constructed, leading to a “super-ratio” (as defined in [8]), taken into account. Reconstructed energy spectrum, with detector response effects overlaid is the Monte Carlo predicted measured background (signal:background). Also overlaid is the Monte Carlo prediction. The measured background spectrum is also shown. Middle: $A_0$ vs $E_{\text{recon}}$, shown with statistical error bars, and fit to a constant from 220 to 670 keV. Bottom: corrections and their uncertainties (band) excluding polarization and theory contributions; positive sign indicating a larger $|A_0|$.

For each run, events are binned based on reconstructed energy (10 keV bins) and initial direction. The rates in the two detectors are then computed based on the experiment live time. We applied separate spin-dependent blinding factors to the two detector rates, effectively adding an unknown scaling factor into the measurement. To extract $A_0$, we first divide the raw measured asymmetry by $\beta$ in each energy bin to remove the strongest sensitivity dependence. As described in [7,8], two scattering related effects dominate subsequent systematic corrections: the residual backscattering correction $\Delta_{\text{backscattering}}$ and the angle effect $\Delta_{\text{angle}}$. In addition to a small correction due to incorrect identification of the initial electron direction for the measured electron backscatters (where both detectors observe the electron), there are corrections for backscattering from the decay trap windows and the front windows of the MWPC that cannot be identified experimentally. Angle effects arise from the fact that the energy loss of an electron in the thin windows is strongly angle dependent. Low-energy, large pitch angle electrons are more likely to fall below the scintillator threshold, leading to a suppression of the acceptance at large angles. Both of these effects were evaluated with two independent Monte Carlo simulation packages: PENelope [18] and GEANT4 [19] (version 4.9.5, using the Livermore low-energy electromagnetic physics model [20]). The two simulations were benchmarked against the measured backscattering distributions for the different types of backscattering events using both neutron $\beta$-decay electrons and conversion-electron sources. The resulting corrections are shown in Table II. For all analysis choices (inclusion or exclusion of backscattering event types), the correction calculated from the two Monte Carlo models agreed to within 15%. Based on observed differences between the simulations and the detectable backscattering data (e.g., two scintillator triggers and two MWPC hits for single scintillator triggers), we assign a fractional uncertainty of 25% to the backscattering and angle effect corrections.

Additional theoretical contributions (beyond the simple $v/c$ term) must be incorporated in order to convert the observable neutron $\beta$ decay asymmetry $A(E)$ to the underlying parameter $A_0$. Recoil-order contributions to $A(E)$ were calculated within the context of the standard model according to the formalism of [21–24], and the radiative correction contribution was calculated according to [25–27].

For an analysis that extracts $A_0$ as a function of energy, the bin-by-bin energy dependence. As described in [7,8], two scattering related effects dominate subsequent systematic corrections: the residual backscattering correction $\Delta_{\text{backscattering}}$ and the angle effect $\Delta_{\text{angle}}$. In addition to a small correction due to incorrect identification of the initial electron direction for the measured electron backscatters (where both detectors observe the electron), there are corrections for backscattering from the decay trap windows and the front windows of the MWPC that cannot be identified experimentally. Angle effects arise from the fact that the energy loss of an electron in the thin windows is strongly angle dependent. Low-energy, large pitch angle electrons are more likely to fall below the scintillator threshold, leading to a suppression of the acceptance at large angles. Both of these effects were evaluated with two independent Monte Carlo simulation packages: PENelope [18] and GEANT4 [19] (version 4.9.5, using the Livermore low-energy electromagnetic physics model [20]). The two simulations were benchmarked against the measured backscattering distributions for the different types of backscattering events using both neutron $\beta$-decay electrons and conversion-electron sources. The resulting corrections are shown in Table II. For all analysis choices (inclusion or exclusion of backscattering event types), the correction calculated from the two Monte Carlo models agreed to within 15%. Based on observed differences between the simulations and the detectable backscattering data (e.g., two scintillator triggers and two MWPC hits for single scintillator triggers), we assign a fractional uncertainty of 25% to the backscattering and angle effect corrections.

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Table II. Summary of corrections and uncertainties as % of $A_0$. “+” corrections increase $|A_0|$ from the observed uncorrected value.

<table>
<thead>
<tr>
<th>Correction</th>
<th>Corr. (%)</th>
<th>Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>+0.67</td>
<td>±0.56</td>
</tr>
<tr>
<td>$\Delta_{\text{backscattering}}$</td>
<td>+1.36</td>
<td>±0.34</td>
</tr>
<tr>
<td>$\Delta_{\text{angle}}$</td>
<td>−1.21</td>
<td>±0.30</td>
</tr>
<tr>
<td>Energy reconstruction</td>
<td>±0.31</td>
<td></td>
</tr>
<tr>
<td>Gain fluctuation</td>
<td>±0.18</td>
<td></td>
</tr>
<tr>
<td>Field non-uniformity</td>
<td>±0.10</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{MWPC}}$</td>
<td>+0.12</td>
<td>±0.08</td>
</tr>
<tr>
<td>Muon veto efficiency</td>
<td>±0.03</td>
<td></td>
</tr>
<tr>
<td>UCN-induced background</td>
<td>+0.01</td>
<td>±0.02</td>
</tr>
<tr>
<td>$\sigma_{\text{statistics}}$</td>
<td>±0.46</td>
<td></td>
</tr>
</tbody>
</table>

Theory contributions

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoil order [21–24]</td>
<td>−1.71</td>
<td>±0.03</td>
</tr>
<tr>
<td>Radiative [25,26]</td>
<td>−0.10</td>
<td>±0.05</td>
</tr>
</tbody>
</table>

The estimated radiative correction in [25], Eq. (15), is based on an energy-independent analysis that integrates total counts across the whole spectrum. The “Fermi function” weighting of the spectrum toward lower energies (and lower asymmetry), represented by the Coulomb terms $2\pi^2\beta^{-1}$ in [25], Eq. (14), dominates the correction. For an analysis that extracts $A_0$ as a function of energy, the bin-by-bin energy-dependent correction has the opposite sign. Our previous $A_0$ measurement [9] did not account for this. Updating the result with the value from Table II modifies the result from [9] to $A_0 = -0.11942 \pm 0.00089^{+0.00123}_{-0.00140}$.  

FIG. 1. Top: background subtracted electron energy spectrum, combining both detector sides and spin states, overlaid with the Monte Carlo prediction. The measured background spectrum is also shown. Middle: $A_0$ vs $E_{\text{recon}}$, shown with statistical error bars, and fit to a constant from 220 to 670 keV. Bottom: corrections and their uncertainties (band) excluding polarization and theory contributions; positive sign indicating a larger $|A_0|$.
Applying all corrections mentioned above, the extracted $A_0$ is plotted against $E_{\text{reco}}$ in the middle panel of Fig. 1. Energy-dependent corrections (backscattering and angle effects) and their uncertainty are indicated in the figure. The final $A_0$ is obtained from an average over an energy range of 220–670 keV, which was chosen, before unblinding the asymmetries, in order to minimize the combined statistical and systematic uncertainties. In the 220–670 keV range, fitting the 10 keV binned values of $A_0$ to a constant value yields $\chi^2/\text{ndf} = 41.7/44$ (based on statistical error bars). The energy-averaged $A_0$ is also very stable for different energy ranges, remaining constant within ±0.15% for ranges out to 100–800 keV (where $\chi^2/\text{ndf} = 68.2/69$).

The uncertainties and systematic corrections to $A_0$ are summarized in Table II. The measured result is $A_0 = -0.11954(15)$ which includes the result of A0 from this work (filled square) and the combined result of [7,9] and this work of [10] and [32] as discussed in the text. The gray band indicates the PDG 2012 average value of $A_0 = -0.1176(11)$ [33], which includes the results of [7,9,28–31], but does not include [32] or the work reported here.

In summary we have measured the polarized neutron decay asymmetry with UCNs resulting in a fractional precision of $\sigma_{A}/A < 2\%$. When combined with our previous precision result [9] with the updated radiative contribution, we obtain a UCNA value of $A_0 = -0.11952(110)$ and $\lambda = -1.2755(30)$. The consistency of our results with the most recent measurements from the Perkeo Collaboration [31,32], which have significantly smaller corrections compared to the pre-2000 results, may suggest that the uncertainties were underestimated in some of these earlier experiments. This consistency of the most recent values of $\lambda$ in the context of light quark decay parameters is shown in Fig. 3.

With considerable efforts underway worldwide to improve the precision of angular correlation measurements sensitive to $\lambda$ using cold neutron beams [34–38], there remains significant motivation to continue efforts to further refine corresponding measurements with UCNs.

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[27] F. Glück (private communication).